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LIMITING HARDENING STRESS LEVELS IN SHEET GLASS

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The limiting level of sheet glass hardening is presented based on three classification strength criteria and is equal to about 500 MPa.

Hardening of sheet glass is the most radical method among the strengthening methods currently used. Air-jet hardening, which is commonly used in the industry, provides for a regular 4 – 5 times strength increase and imparts additional useful properties to glass (safe fracturing, increased heat resistance).

I. A. Boguslavskii [1] claimed that a strength level of 1000 MPa had been reached under a rather complex integrated impact. Compared with the mean statistical level of sheet glass strength equal to 75 MPa, the reported result is 13.3 times stronger. R. Gardon [2] expressed a cautious doubt regarding this statement.

It is clear that despite all the technological devices, the strength of glass will be far from the theoretical value

$$\sigma_{th} = 0.1E,$$

where E is the Young modulus.

For window glass, $E \approx 0.7 \times 10^5$ MPa, i.e., $\sigma_{th} \approx$ 7000 MPa, but the problem of the degree of approaching this value in the course of hardening is a topical problem both in its theoretical and technological aspects.

If we exclude for further consideration several factors of the industrial glass-hardening process, a hardened glass plate and the hardening stresses induced in this plate can be represented as a simplified model (Fig. 1). The plate has a size of $L \times B$ and thickness d. The hardening stresses are represented by the epures σ_x and σ_y, and the stress $\sigma_z = 0$.

Each of these epures has a generally known configuration described by a quadratic parabola:

$$\sigma_x(z) = \sigma_y(z) = \sigma(0)\left(1 - \frac{12z^2}{d^2}\right), \tag{1}$$

where $\sigma(0)$ is the central stretching stress.

Based on expression (1) it is easy to determine the surface stress

$$\sigma_s = -2\sigma(0) \tag{2}$$

and the coordinate position of zero stresses

$$z = \pm 0.289d. \tag{3}$$

It is understood that the relationships (1) – (3) are only an initial approximation to the actual stress distribution, which is more accurately described by the relaxation theory of Narayanasvami – Mazurin [3]; however, we will regard them as sufficient for initial solving of the limiting hardening conditions.

The main prerequisite for subsequent conclusions is the possibility of self-destruction of an article under the effect of induced hardening stresses, and since a destruction always starts from the surface, our main focus will be on the stressed state of the surface layers under a preset technological effect.

Thus, the strength of hardened glass is determined only by the induced surface stress, which depends on the process parameters: the glass thickness d, the heat-transfer coefficient in cooling α, the hardening temperature $t(0)$, etc.

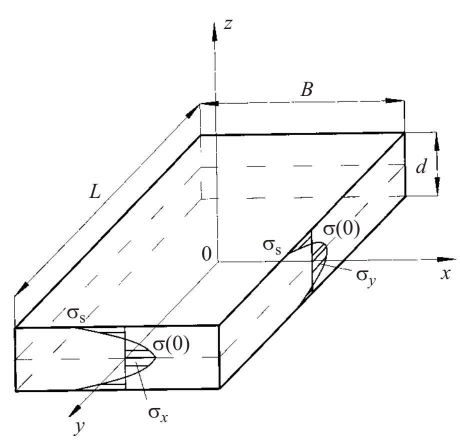

Fig. 1. Scheme of hardening stress formation.

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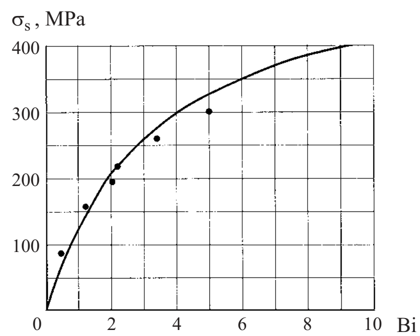

Fig. 2. Relationship between surface stresses in hardened glass and the Biot number: solid line) according to G. M. Bartenev [4]; dots) according to E. Mikhalik and S. Ohlberg [5].

At the same time, the issue of the ultimate possibilities of the process arises with respect to the strength products.

Since destruction always starts from the surface, a hypothesis was proposed that the limiting stress value for hardened glass is determined by the level of surface stress σ_s in hardening, which itself is capable of destroying the product. When the limiting value of σ_s is calculated, one can talk of the ultimate process parameters, which it would be meaningless to exceed.

We can take as a control parameter, for instance, the limiting value of the Biot number $\mathrm{Bi}_{\mathrm{lim}}$ under glass cooling at a technologically reasonable hardening temperature $t(0)$.

According to G. M. Bartenev [4], the stress in the central plane of hardened glass in the first approximation can be determined from the following relationship:

$$\sigma(0) = \frac{\beta E}{2(1-\mu)} t_g \frac{\mathrm{Bi}}{3+\mathrm{Bi}},$$

where β is the temperature coefficient of expansion of glass, μ is the Poisson coefficient, t_g is the vitrification temperature, Bi is the Biot number, where

$$\mathrm{Bi} = \frac{\alpha d}{2\lambda},$$

where α is the coefficient of heat transfer from the glass surface to the cooling agent in hardening and λ is the thermal conductivity of glass.

The surface stress in hardened glass according to expression (2) and not considering the sign is

$$\sigma_s = \frac{\beta E}{1-\mu} t_g \frac{\mathrm{Bi}}{3+\mathrm{Bi}}. \qquad (4)$$

Set the mean weighted values of the physical constants in expression (4): $\beta = 11.2 \times 10^{-6}\ \mathrm{K}^{-1}$, $E = 0.68 \times 10^6$ MPa, $\mu = 0.22$, and $t_g = 540°\mathrm{C}$; then

$$\sigma_s \approx 527 \frac{\mathrm{Bi}}{3+\mathrm{Bi}}.$$

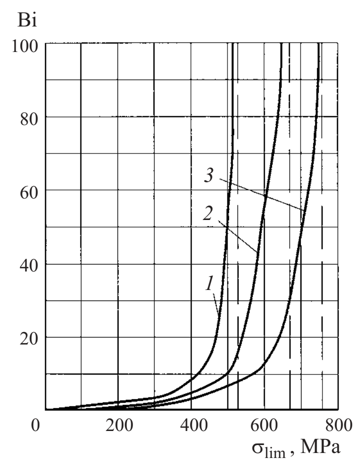

Fig. 3. The ultimate value of the Biot number depending on the ultimate level of hardening stress: *1*, *2*, and *3*) $\sigma_{\mathrm{lim}} = 527$, 658, and 745 MPa, respectively.

The dependence $\sigma_s = f(\mathrm{Bi})$ is shown in Fig. 2. It can be seen that within the range of relatively small values of the Biot number, nearly all results coincide, and in the range of Bi > 2, Bartenev's method yields an exaggerated value of σ_s. Thus, in solving the problem of the ultimately possible level of hardening, the results according to G. M. Bartenev yield a certain reserve of reliability for subsequent calculations.

For an objective evaluation of the possibility of self-destruction of glass due to its internal stresses, three criteria of strength were used [6]:

– the criterion of the highest normal stress;

– the energy criterion (Beltramy);

– the criterion of complete specific deformation (Giber – Mises – Genky).

The destruction condition in the first case is the equality of the surface stress to a certain ultimate value: $\sigma_s = \sigma_{\mathrm{lim}}$. In this case $\mathrm{Bi} = \mathrm{Bi}_{\mathrm{lim}}$. Taking into account relationship (4), we have

$$\sigma_{\mathrm{lim}} = \frac{\beta E}{1-\mu} t_g \frac{\mathrm{Bi}_{\mathrm{lim}}}{3+\mathrm{Bi}_{\mathrm{lim}}}.$$

By denoting

$$\frac{\beta E}{1-\mu} t_g = C$$

and performing the necessary transformations, we obtain

$$\mathrm{Bi}_{\mathrm{lim}} = \frac{3\sigma_{\mathrm{lim}}}{C - \sigma_{\mathrm{lim}}},$$

and as the Biot number cannot be an infinite value, $\sigma_{\mathrm{lim}} < C = 527$ MPa.

Similar transformations based on the energy criterion established that $\sigma_{lim} < 745$ MPa, and based on the complete specific deformation criterion, $\sigma_{lim} < 658$ MPa.

At the same time, the dependence of the Biot number on the limiting level of hardening stress was obtained (Fig. 3).

Since the contemporary evaluation of the effectiveness of various strength criteria is rather contradictory, one can with a certain reservation determine the limiting strength of hardened glass as 500 MPa, which is half as much as the value predicted by I. A. Boguslavskii.

Based on the plot shown in Fig. 3 and the highest normal stress criterion, it is easy to determine the maximum possible technological impact in the form of Bi = 50.

The proposed method, moreover, makes it possible to theoretically substantiate the analytical determination of the heat resistance of glass when its physical constants and the hardening stress level are set.

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